Kinetic Energies in Multifragmentation

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ABSTRACT

Energy spectra for fragments and light particles from target spectators produced in collisions of ^{197}Au + ^{197}Au at 1000 MeV per nucleon have been measured. In the case of nucleons and α particles, a low-temperature equilibrium component and a high-temperature component can be distinguished. For the remaining fragments with $2 \leq A \leq 10$, the kinetic-energy spectra exhibit slope temperatures of about 17 MeV, independent of the particle species and including the high-temperature α component. It is suggested that these slope temperatures may reflect the intrinsic Fermi motion of the system prior to its decay and it is shown that, in this way, a consistent understanding of the slope temperatures and of the much lower emission temperatures, as deduced from isotope ratios, can be obtained.

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1 Introduction

A study of multifragmentation will quite naturally start with the detection of nuclear fragments and their identification as reaction products different from typical evaporation particles and lighter than conventional products of binary fission. Already the emission frequencies of these fragments of intermediate mass and the multiplicity correlations characterizing the populated partition space are of considerable interest. The observed fragment-charge correlations exhibit universal features [1] that nuclear multifragmentation, apparently, has in common with a variety of non-nuclear disintegration processes and even with purely mathematical models [2]. The example of the fragmentation of hydrogen clusters has been presented by B. Farizon at this Winter Meeting [3]. Many characteristics of the mass correlations reported there are familiar from multifragmentation experiments.

Kinetic energies become important as soon as one goes beyond the partition space and starts to explore the dynamical and statistical properties of the fragmentation mechanism. More than one half of the excitation energy residing in the decaying complex reappears in the form of kinetic energy of the produced particles and fragments [4]. Calorimetric methods have been developed to reconstruct this excitation energy [5, 6], relying on the assumption that all recorded particles are generated during the multifragment breakup. Kinetic energy spectra, furthermore, may permit the distinction between thermal and collective components in the fragment motion which in turn is essential for the understanding of the underlying mechanisms [7]. They are essential also for the search of signals of the liquid-gas phase transition following the method recently proposed by Chomaz and Gulminelli [8]. The precise experimental knowledge of kinetic energies on an event-by-event basis is indispensable for the application of the fluctuation methods suggested there [9].

Spectator decays following peripheral heavy-ion collisions at relativistic energies are characterized by the observation of equilibrium properties in most observables. The fragment yields and correlations are independent of the specific properties of the entrance channel and can be described with high accuracy with the statistical multifragmentation models [10, 11]. The breakup temperatures required for the model description are in good agreement with measured isotope temperatures, and the isotopic yields from which these temperatures are derived are well accounted for [12, 13].

With the same set of model parameters, on the other hand, the mean kinetic energies of particles and fragments are far from being reproduced with comparable accuracy [1, 12]. Measured kinetic energies or, equivalently, the slope temperatures obtained from Maxwell-Boltzmann fits to the kinetic energy spectra have been found to considerably exceed the predicted values, even though the effects of Coulomb repulsion and sequential decay are included in the model description. The qualitative difference between the chemical or thermal equilibrium temperatures and the kinetic temperatures has been observed for a variety of reactions and numerous reasons for it have been presented [14-19]. Preequilibrium or pre-breakup emissions are likely explanations for high-energy components in light-particle spectra [12,20-22]. In some cases, the excess kinetic energies have been ascribed to collec-

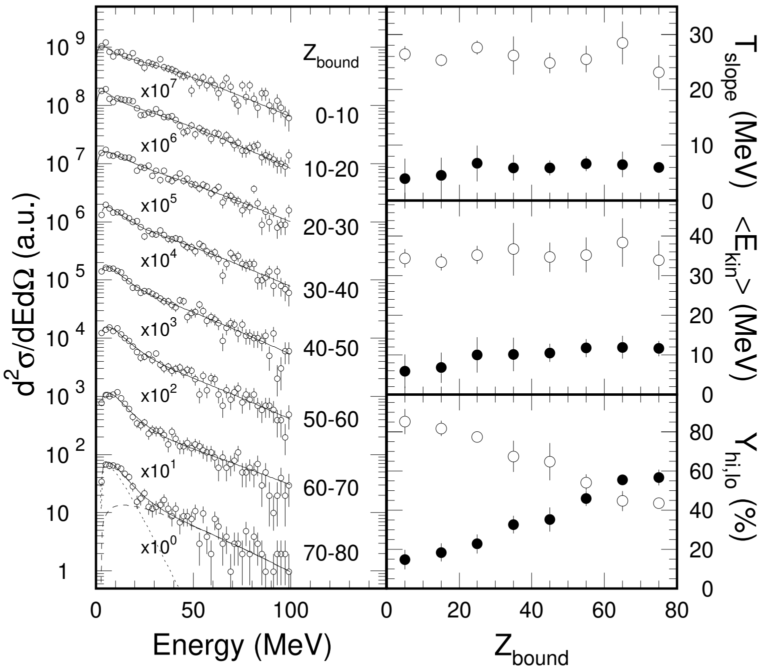

Figure 1: Proton energy spectra measured at $\theta_{lab} = 150^{\circ}$ (left panel) and slope temperatures, mean kinetic energies, and relative yields of the two components with high (open circles) and low (closed circles) temperatures (right panels). The full lines represent the fit results, the dashed and dotted lines give the high and low temperature components for $70 \leq Z_{bound} \leq 80$ individually. Note that the fitting was performed with the assumption that two components exist which, for $Z_{bound} \leq 30$, is not unambiguously supported by the data.

tive flow even though a characteristic proportionality to the fragment mass is not evident in the data [23-25]. Other authors were caused by this situation to more generally question the applicability of statistical descriptions for spectator fragmentation [26]. An explanation in terms of the Goldhaber model [27] that will be presented in the following has been suggested long ago [15, 28] but, so far, has not been generally adopted.

2 Experimental method

The experiments were performed at the ALADIN spectrometer [1] with beams of ^{197}Au of 1000 MeV per nucleon incident energy and ^{197}Au targets of 25-mg/cm^2 areal thickness. As part of a larger experimental setup [12, 29, 30], three high-resolution telescopes were placed at backward angles for detecting the products of the target-spectator decay. Each telescope consisted of three Si detectors with increasing thickness and was backed by a CsI(Tl) scintillation detector. Isotopes in the range from hydrogen to carbon were satisfactorily resolved.

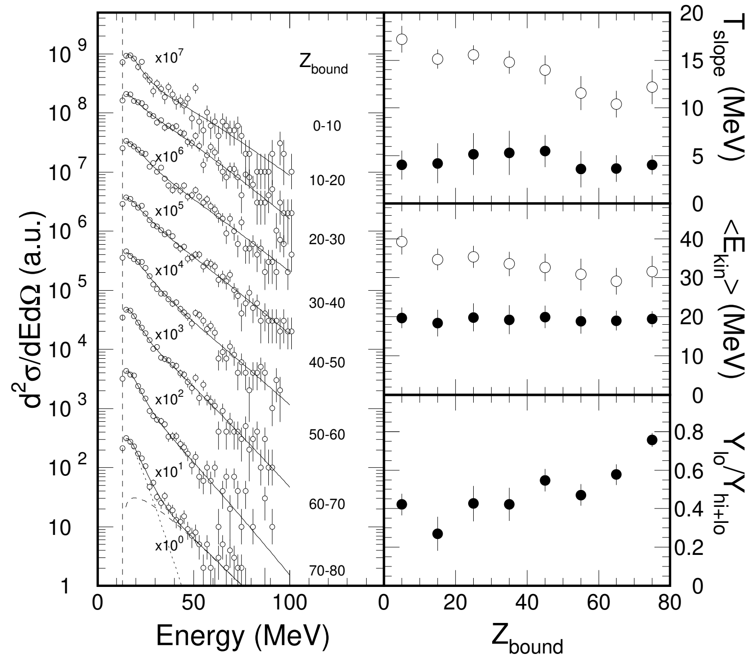

Figure 2: Energy spectra and derived properties (same as in Fig. 1) of α particles measured at $\theta_{lab} = 150°$.

The products of the projectile decay were measured with the time-of-flight wall of the ALADIN spectrometer [1] and Z_{bound} was determined event-by-event. The sorting variable Z_{bound} is defined as the sum of the atomic numbers Z_i of all projectile fragments with $Z_i \geq 2$. Z_{bound} is close to the total charge of the original spectator system and therefore also correlated with the impact parameter of the reaction. Because of the symmetry of the collision system, the mean values of Z_{bound} for the target and the projectile spectators within the same event class have been assumed to be identical. First results of these measurements have been presented in Ref. [12, 31].

3 Light charged particles

The kinetic-energy spectra of protons (Fig. 1) appear as a superposition of two components of which the soft component is most clearly identified at large Z_{bound}. Fits using two Maxwellians yield temperature parameters of very different magnitude that both are nearly independent of Z_{bound} (Fig. 1, right panels). The slope temperature T of about 5 to 7 MeV of the soft component is of the same order as the measured breakup temperatures [12]. The intensity of this component is strongly correlated with Z_{max}, the largest atomic number of the partition, which supports its interpretation as evaporation from highly excited residual nuclei [32].

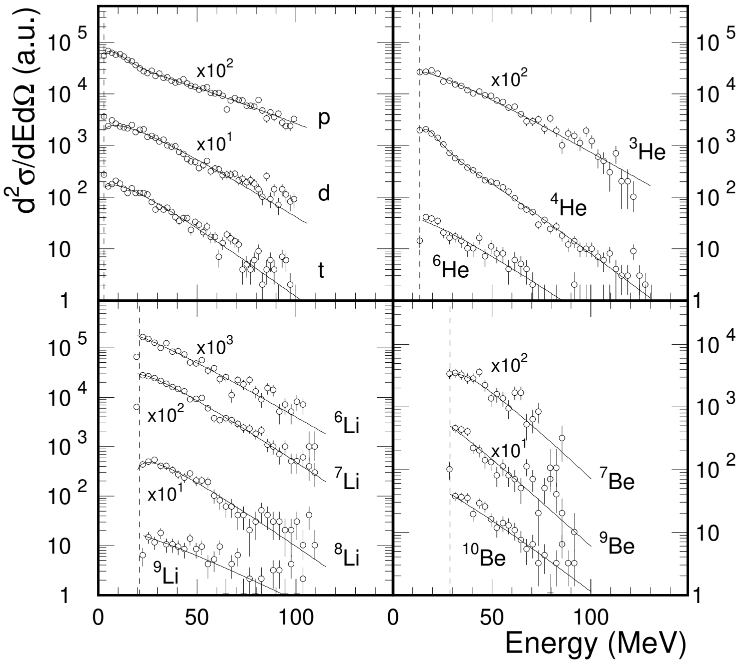

Figure 3: Energy spectra of light charged particles and fragments with $Z \leq 4$ integrated over $20 \leq Z_{bound} \leq 60$ ($\theta_{lab} = 150°$). The full lines represent the fit results, the dashed lines indicate the trigger threshold of the 300-μm detector. The same normalization is used for all spectra.

Also the spectra of α particles (Fig. 2) and of neutrons, measured with LAND [33], permit the distinction of two components of which the low-temperature component seems typical for evaporation. The high-temperature components of protons and neutrons appear to have their origin not only in the breakup stage but also in the earlier cascading stages of the collision. This is supported by the two observations that (i) their slope parameters are rather large and, as established for the neutron case, vary with the bombarding energy and (ii) that the observed multiplicities are about twice as large as those predicted by the statistical multifragmentation model [32].

4 Kinetic energies of fragments

Kinetic energy spectra of products with mass numbers $A \leq 10$ are shown in Fig. 3, integrated over the interval $20 \leq Z_{bound} \leq 60$. Apart from the proton and ^{4}He cases discussed above, they have the shapes of single-component Maxwellians to a good approximation, and the corresponding slope temperatures were obtained from fits with three-parameter functions that included a Coulomb potential V_c. The results are given in Fig. 4 where, for protons and ^{4}He, the values of the high-temperature components are shown. The high proton temperature $T \approx 26$ MeV is consistent with its interpretation as being generated

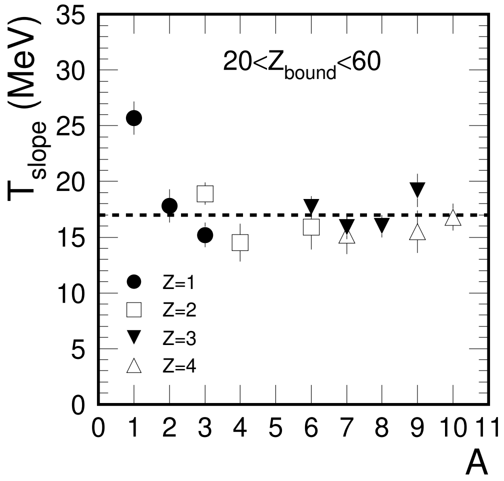

Figure 4: Slope temperatures for isotopically resolved charged particles and fragments, measured at $\Theta_{lab} = 150^{\circ}$ and integrated over $20 \leq Z_{bound} \leq 60$, as a function of the mass number A. For protons and α particles the value of the high-temperature component is shown.

during the initial cascading stages of the reaction. All other spectra exhibit temperatures that are narrowly dispersed around a mean value of 17 MeV, including the ^{3,4}He isotopes (cf. [34]).

A mass-invariant temperature is usually taken as indication for equilibration of the kinetic degrees of freedom. On the other hand, Coulomb effects should contribute in proportion to the fragment charge, recoil effects may be important for heavier fragments, and the small but finite motion of the target spectator should introduce a collective velocity component. In order to estimate the magnitude of these effects, a model study was performed which started from initial configurations generated by randomly placing fragments and light particles in a spherical volume with random momenta corresponding to a given temperature T. Experimental charge distributions from Ref. [1] and an average density $\rho/\rho_0 = 0.3$ were used where ρ_0 is the normal nuclear density. N-body Coulomb trajectory calculations were then performed and asymptotic slope temperatures were determined by fitting, following the same procedure as with the experimental data.

The results for $T = 15$ MeV, shown in Fig. 5, illustrate the individual contributions of Coulomb repulsion and of the source motion. They demonstrate that, in the present case, the considered effects are relatively small, perhaps of the order of $\Delta T/\Delta A \approx 0.2$ MeV, and that they cancel each other to a very good approximation. The asymptotic slope parameters have the same value of 15 MeV as the temperature of the starting configuration. We therefore conclude that the measured slope parameters of $T \approx 17$ MeV (Fig. 4) are equal to the temperatures to be used in a thermal interpretation of the data.

The model study also showed that the Coulomb repulsion contributes considerably to the final kinetic energies (Fig. 5, right panel). The resulting mean kinetic energies in the

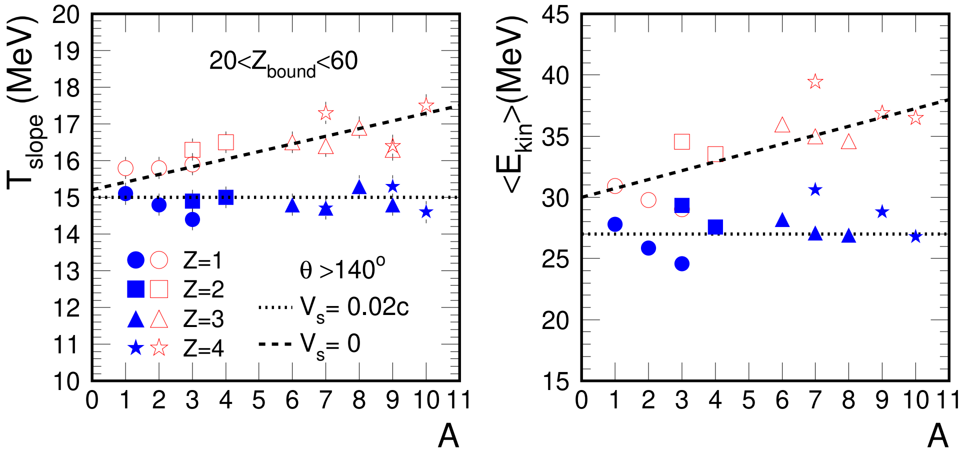

Figure 5: Results of the model study for the decay of a thermalized source with temperature $T = 15$ MeV. The slope temperatures (left panel) and the mean kinetic energies (right panel) for $\Theta_{lab} \geq 140°$ are shown as a function of A and for sources at rest in the laboratory (open symbols, dashed line) and moving with $\beta = 0.02$ in beam direction (full symbols, dotted line).

center-of-mass frame of the decaying system add up to about 35 to 40 MeV, quite consistent with values obtained in earlier experiments where kinetic energies were derived from the widths of momentum distributions of projectile fragments [1]. In these experiments, the mean kinetic energies were found to be approximately constant over the range of fragment atomic number $Z \ \leq 20$.

5 Effects of Fermi motion

The potential role of the nucleonic Fermi motion within the colliding nuclei in generating the fragment momenta in fast disintegration processes has been discussed by Goldhaber many years ago [27]. He also pointed out that the resulting behavior is indistinguishable from that of a thermalized system with rather high temperature. For the Fermi momentum $p_F \approx 265$ MeV/c of heavier nuclei the corresponding temperature is $T = 15$ MeV. This seems very close to the mean slope temperatures $T = 17$ MeV displayed in Fig. 4.

The initial idea, formulated for cold nuclei, has been followed up by Bauer who has extended it to the case of expanded fermionic systems at finite temperature [19]. We have used the numerical solution reported there by assuming that the temperature of the system is given by the measured breakup temperatures $T_{\rm HeLi}$, derived from the yields of ^{3,4}He and ^{6,7}Li isotopes [6, 12, 35]. For the breakup density two alternative values $\rho/\rho_0 = 1.0$ and 0.3 were chosen which correspond to two significantly different scenarii for the process of fragment production. The higher value is expected for a fast abrasion stage that will induce fragmentation of the residual spectators but not instantly affect the nucleon motion within them. The lower value is in the range usually assumed for multi-fragment breakups of

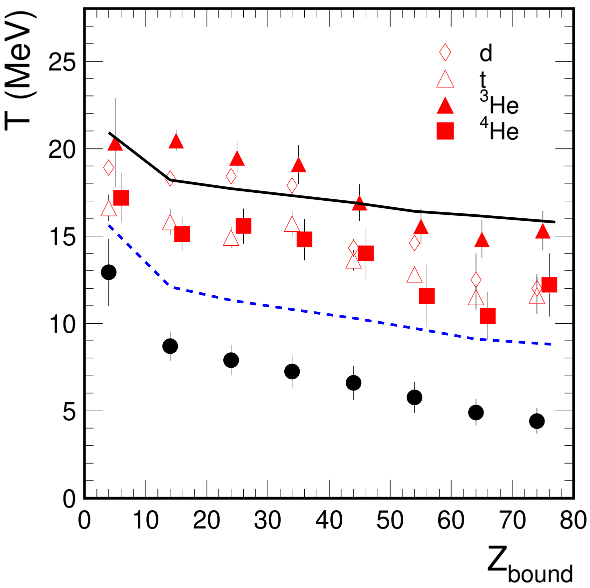

Figure 6: Slope temperatures for light charged particles of mass $2 \leq A \leq 4$ (squares, triangles and diamonds) and the isotope temperature T_{HeLi} (dots) as a function of Z_{bound}. The lines give the predictions for the fast breakup of a Fermi gas with finite temperature T_{HeLi} and with densities $\rho/\rho_0 = 1.0$ (full line) and 0.3 (dashed).

expanded systems [10, 11]. Here the development of instabilities, as the system enters the spinodal region, will also cause a rapid fragmentation, so that the nucleonic Fermi motion will contribute to the fragment kinetic energies. For a homogeneous system at a lower than normal density the Fermi motion is reduced and the effect will be smaller.

The obtained results are represented by the lines shown in Fig. 6. The comparison with the data is here restricted to the $A \leq 4$ isotopes for which the collected statistics are sufficient for studying the Z_{bound} dependence. The recoil factor $(A_s - A)/(A_s - 1)$ appearing in the Goldhaber formula [19, 27] can be safely ignored as the mass number A_s of the spectator system is 100 to 150 on average and still about 50 in the bin of smallest Z_{bound} [6]. Qualitatively, the predicted values are close to those observed. In particular, the rise with decreasing Z_{bound} follows as a consequence of the rising breakup temperatures T_{HeLi}. Apparently, with assumptions as made in the Goldhaber model, the two different types of temperatures are mutually consistent. The role of the slope temperatures, consequently, is restricted to describing the fragment motion while T_{HeLi} is the more suitable observable for representing the temperature of the nuclear environment at the breakup stage.

Recent calculations with transport models, which incorporate Fermi motion, support this interpretation [26, 36, 37]. The energies of spectator fragments, as measured in the present reaction, are well reproduced, and the coexistence of qualitatively different internal (or local) temperatures and fragment slope temperatures has been demonstrated in these

QMD and BUU studies. On the experimental side, the observed similarity of fragment kinetic energy spectra, measured with different projectiles at various incident energies, is expected from the Goldhaber model [1,15,25,28,38-40]. The fluctuations corresponding to the higher slope temperatures may also explain the observed large widths of the intrinsic kinetic-energy distributions in ^{197}Au fragmentation at 600 MeV per nucleon that are not easily reproduced with statistical multifragmentation models [41].

A more quantitative comparison with the data shown in Figs. 4 and 6 will favor the prediction for $\rho/\rho_0 = 1.0$ corresponding to a fast breakup over that for $\rho/\rho_0 = 0.3$ that is reached after a homogeneous expansion. This would not be unexpected in the present case of spectator fragmentation following collisions of heavy ions and might indicate a limited resilience of nuclear matter to shape deformations [42]. The cited QMD and BUU calculations consistently suggest that the fragments are preformed at an early stage of the collision ($\leq$ 50 fm/c) before the system has expanded to typical breakup densities.

6 Concluding remarks

It would certainly be premature to draw firm conclusions regarding the mode of fragment formation from the present data alone. The role of secondary decays and possibly other effects will have to be considered, and a moderate collective velocity component as a result of thermal expansion cannot be completely excluded [43], even though it is not explicitly indicated for the present reaction (Fig. 4 and [1]). We mainly like to point out that, within the Goldhaber picture of a random superposition of the nucleon momenta, the larger slope temperatures are fully consistent with a breakup at equilibrium temperatures of 6 to 8 MeV, as they are measured and predicted by the statistical multifragmentation models. The additional sensitivity to the fragmentation mechanism, via the density at which the Fermi motion has been established, makes this interpretation attractive for further studies.

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